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MONITORING FOR NATIONAL FOREST PLANS

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MONITORING FOR NATIONAL FOREST PLANS

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CONTENTS

	Page
Executive Summary	1
Background	2
Selection of Outputs and Effects for Monitoring	9
What To Do When Things Go Wrong	9
Sample Size for Monitoring	12
Monitoring Cost	15
Allocation of Monitoring Observations	16
Sample Size With Multiple and Self-correlated Outputs and Effects	17
Calculation of An Optimal Monitoring Policy	19
References	20

EXECUTIVE SUMMARY

In this report a rationale for developing a National Forest level monitoring system is established. Two kinds of monitoring are identified (1) examination of practices to determine whether or not implementation is in accordance with standards and guidelines and (2) sampling procedures to determine if outputs and effects are within acceptable limits. Changes in both standards and guidelines and sampling procedures to determine outputs and effects are described as minor changes which can be treated with plan amendments. Changes either in prescriptons allocated to land areas or in Forest objectives, however, are described as major changes which require plan revisions.

To provide meaningful and reasonable monitoring requirements, standards, and guidelines should specify how practices are to be implemented rather than by the outputs or effects expected. Appropriate standards and guidelines should be described by functional specialists.

Acceptable limits for outputs and effects should be related to changes which could result from management decisions. In general, limits of outputs and effects will be described as linear programming constraints and precision requirements will be most closely related to the Forest Plan by the value of the linear programming slack variable associated with the output or effect; exceeding these limits will probably require a plan revision because a new set of selected prescriptions would be indicated in this case. Rigidly defined outputs and/or effects requirements based on uncertain information will most probably lead to a need for frequent plan revision.

Precision requirements may also be established by other authorities such as state water quality standards; failure to meet these precision requirements may not indicate a change in the set of prescriptions required and, even if established as part of the plan, possibly could be treated with a plan amendment.

Sampling designs for outputs and effects will depend on the statistical variance of the output or effect and the required precision of the result. Methods of computing sample size both for outputs and effects which are considered to be correlated with other outputs and effects are described. The report also shows how sampling costs can be calculated to adjust the present net worth of alternatives for the monitoring program.

An introduction to recursive time series analysis is included for planning teams that want to consider calculations of statistical variance when outputs, effects, and activities are correlated over time. A forthcoming report will describe the design of efficient sampling systems for multivariable time series.

BACKGROUND

Development of a National Forest Plan is a demanding process. The information and personnel required can be staggering, using up very sizable portions of a Forest's resources. Part of the reason the job is so big is the apparent complexity of Forest management. With many different types of land, outputs and effects, and time periods to consider, it is difficult to imagine how the job could be simple.

However, another major reason that plans seem to be necessarily complex is the way plans are conceived. If we plan at any point in time for all possible events that can occur over the next 100 years, and attempt to estimate expected outputs and effects, the results cannot be anything but staggering. Such planning can be called "open loop" (Figure 1). Not only is the planning load excessive, such plans are seldom, if ever, fully implemented.

Such large analyses at a single point in time are not only staggering, but are contrary to the way decision are usually made. Generally, we learn by doing. In fact, we usually learn the most by making mistakes. (If we are especially wise, we learn by the mistakes of others.) As long as we are making mistakes, we can learn and improve, but when we are not making mistakes, it is difficult to learn. Eventually we learn to rely more on relatively certain information, and to place less credence on unreliable information. In control theory jargon, learning from mistakes we didn't plan is called "passive" learning; learning from planned mistakes is called "active" learning. Whether active or passive, however, mistakes and (hopefully) learning will occur. It can be demonstrated that at least passive learning is necessary for high performance and in some cases, depending on the nature of the problem, active learning is necessary.

To best capitalize on mistakes and learning, Forest planning could be conceived as a way to planned learning. Such plans would certainly be different than plans designed to avoid mistakes. Learning oriented plans would be less detailed than "mistake-avoidance" plans, and based on both our intuition and some precepts of control theory eventual performance would be higher.

Learning oriented plans, however, are guaranteed to produce better results only in the long run. In the short-run, mistakes can be very costly. In addition, any National Forest has many commitments which cannot be avoided. Since opportunities for making good healthy mistakes are limited, we should learn the most we can from little mistakes.

In addition to the ability to learn, a procedure is also needed for monitoring and making any necessary corrections to steer along a selected path. With some careful thought, a system could be designed to reduce the planning load, provide a learning experience, and meet monitoring requirements.

One possible way to set up a monitoring system is a "closed-loop" procedure shown in Figure 2. In this procedure, outputs and effects are compared to Forest objectives, and corrections are made when the outputs and effects do not meet the objectives. Although the closed-loop feature is desirable and straightforward, the procedure as outlined has several drawbacks.

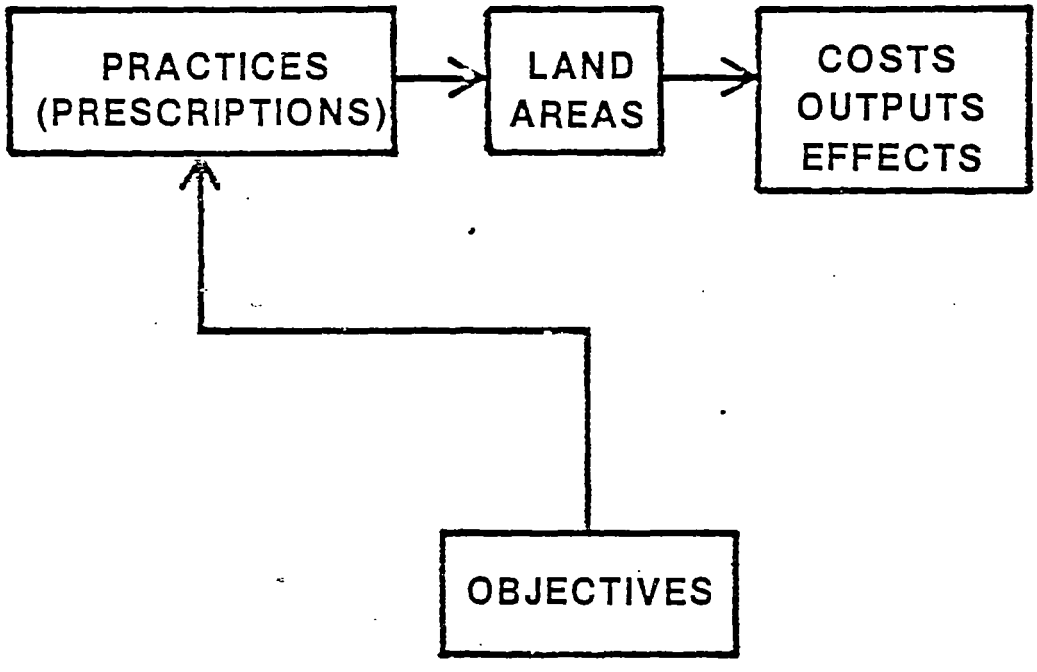

Figure 1.--An "open-loop" system with objectives leading directly to outputs and effects.

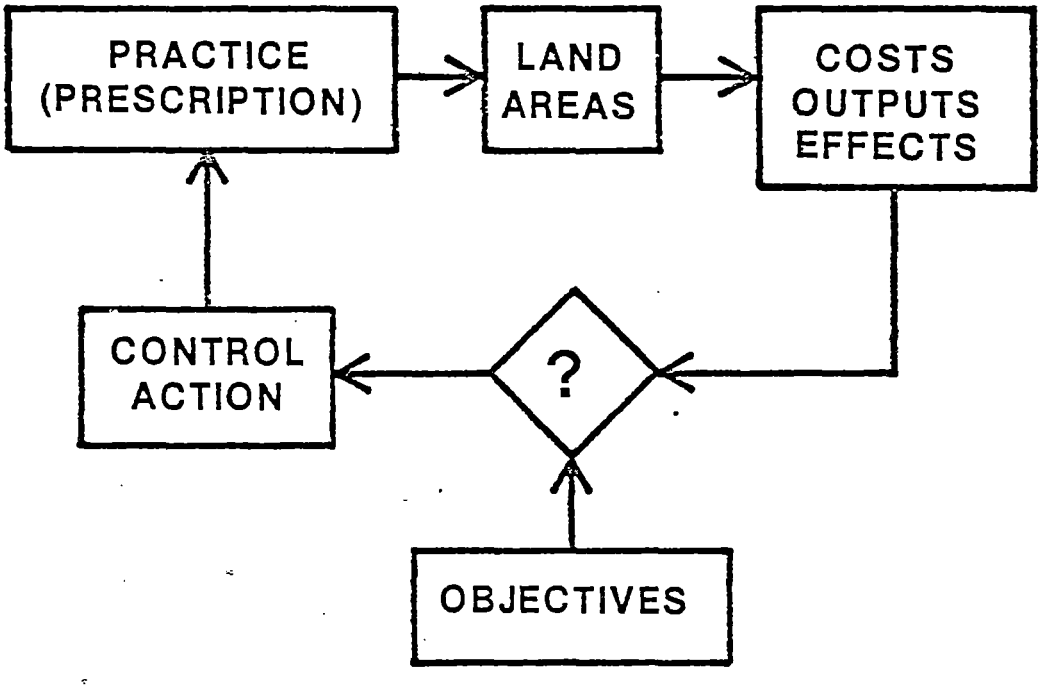

Figure 2.--A "closed-loop" system designed to change management practices to meet objectives.

One difficulty is that practices are not applied singly to land areas; instead they are applied with other practices in prescriptions. Thus, without a careful experimental design it is not possible to distinguish the effects of individual practices. We could, of course, change from monitoring effects of practices to monitoring the effects of prescriptions. At least with this approach it is possible to determine the effects and outputs resulting from the prescriptions. Since prescriptions are assigned to individual land areas, however, determining the effects of individual prescriptions could be a very sizable job indeed. In addition, establishing a management correction procedure on this basis for a typical National Forest would be a very sizable and confusing job. In fact, it is clearly beyond the ability of current (or expected future) control technology.

Monitoring of prescription effects also provides excessive detail. Most Forest objectives are Forest-wide, or at least apply to larger areas than those to which prescriptions are assigned. For example, the nondeclining even-flow concept of timber harvest is both legally and logically required for the entire Forest and other large-scale areas; there is no legal or logical requirement for nondeclining even-flow of individual parcels of land. Water yield requirements may exist for the major drainages, but not for individual streams, and grazing use requirements are for allotments (or larger areas), not for land types within allotments. Thus monitoring of individual prescriptions would result in a more intensive effort than is needed.

To improve on this situation, we can subdivide the monitoring problem into monitoring for accomplishment of practices and monitoring to determine outputs and effects (Figure 3). At the most detailed level, we can inspect the application of practices in accordance with standards and guidelines. At a broader level, such as for the entire Forest or drainage basins, we can monitor for outputs and effects.

With this procedure, we should specify standards and guidelines as to how practices are applied, rather than as to outputs and effects expected. Note that this allows us to inspect practices, and standards for practices can be stated and inspections conducted by functional specialists, if desired. In order to make this level of monitoring useful, however, we do need a system of attainment reports which specifies the geographical location at which practices are implemented. Without such records no inspection of practices would be possible.

It should be emphasized that standards and guidelines be written on expected methods of applying practices. For example, the number of erosion bars per mile of road with a given grade is easily determined by inspection, but the resultant soil loss is much more difficult to determine and should be avoided at this level of detail.

The practice level of monitoring can be adapted or corrected by amending standards and guidelines as necessary. Properly documented with a plan amendment, such changes could ordinarily be considered minor. Some standards and guidelines will, of course, be specified by regional or national directives, and these cannot be changed solely with a Forest plan amendment. Although regional directives may specify standards and guidelines, the application of practices is done at the Forest and district level and this type of monitoring is meaningful only for Forest plans.

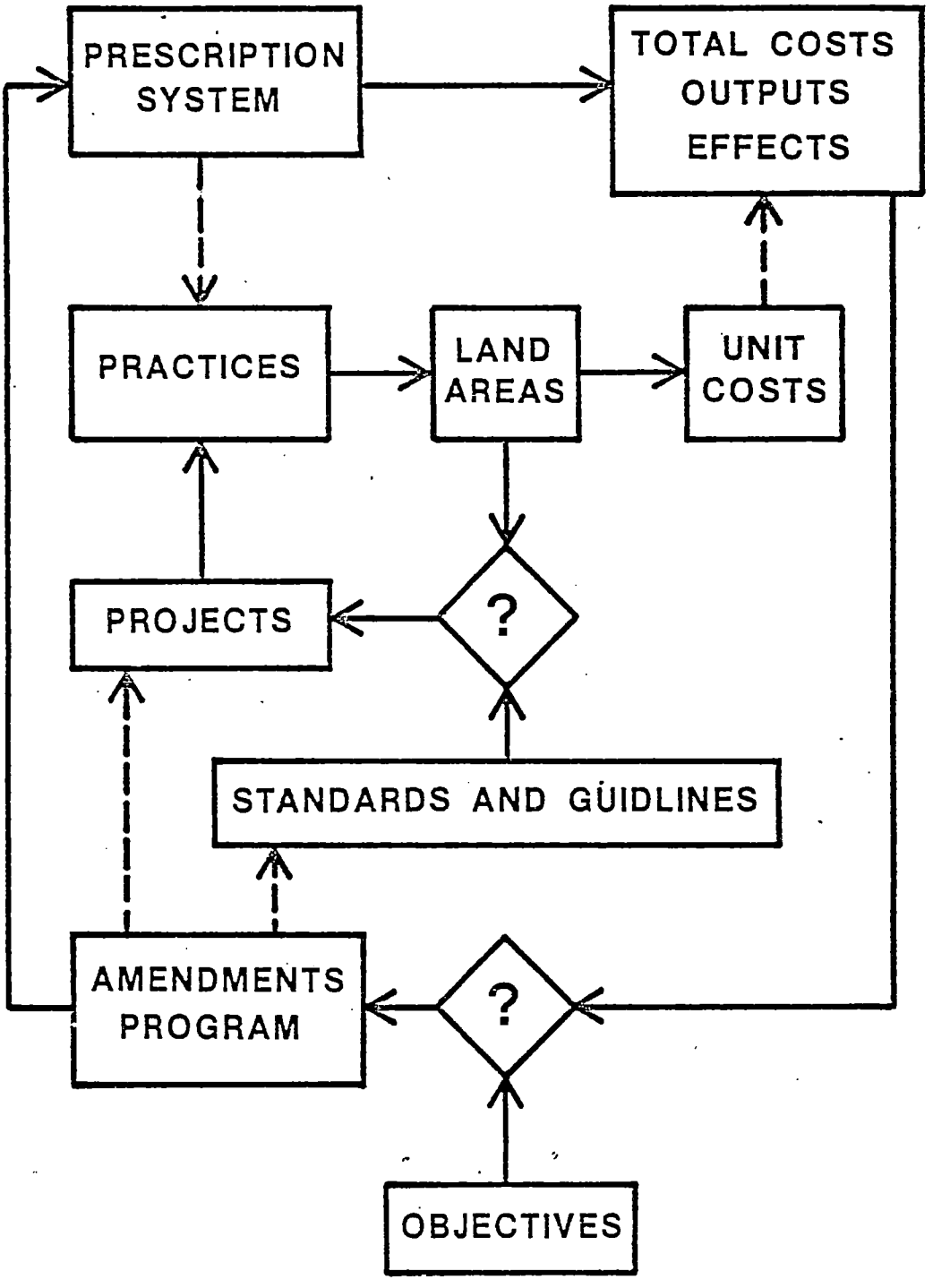

Figure 3.--A two-level monitoring system designed to separate practice implementation from outputs and effects.

The outer loop in Figure 3 compares Forest-wide outputs and effects to Forest objectives. As noted earlier, this is an appropriate level for such a comparison because objectives are written for an entire Forest (or Region in the case of Regional plans). In addition, important savings will result because the sampling requirements for a given level of precision increase less rapidly than does size of area. Thus, it may be no more costly to determine an output to a given level of precision for a Forest than it would be for single capability area.

There is still a difficulty with the approach of Figure 3, however, because any corrective action would necessitate a change in the prescription system which is part of the selected alternative or Forest plan. A change in the selected prescription system would thus require a revision in the Forest plan, and because of planning costs and effort, plan revisions should not be taken lightly. It may be possible to argue that some changes in the prescription system are minor, but with the present methodology of Forest planning there does not appear to be a good analytical basis for concluding that some such changes are minor while others would clearly be major.

There is an additional improvement that can be made, however, and still be within the realm of a minor change; this is in the design of the monitoring or measurement system (Figure 4). Suppose, for example, that we have selected a plan with decade increments; we are willing to revise the plan after 10 years but not sooner. In the meantime, we will inspect the application of practices, tightening or relaxing standards and guidelines as necessary. We also want to establish some sort of measurement system to determine outputs and effects, and we can amend the measurement system (perhaps by increasing or decreasing sample size) as we learn more about measurement errors. Thus both definition of standards and guidelines and definition of the measurement system could be considered minor and handled with amendments, but definition of objectives and selection of a new system of prescriptions would be considered major and would require a plan revision. With the present analytical basis for planning, these distinctions of major and minor seem thoroughly justifiable.

Since the specification of standards and guidelines and inspection of practice implementation require functional expertise, this report will not go into additional detail on practice-level monitoring. It should be pointed out, however, that there will be real costs of inspecting the implementation of practices, and these costs should be included in the total cost of each prescription. Output and effect level monitoring have some common statistical considerations regardless of the output and effect being discussed, and these will be presented in the next section. In addition, methods of calculating the cost of monitoring for outputs and effects will be included.

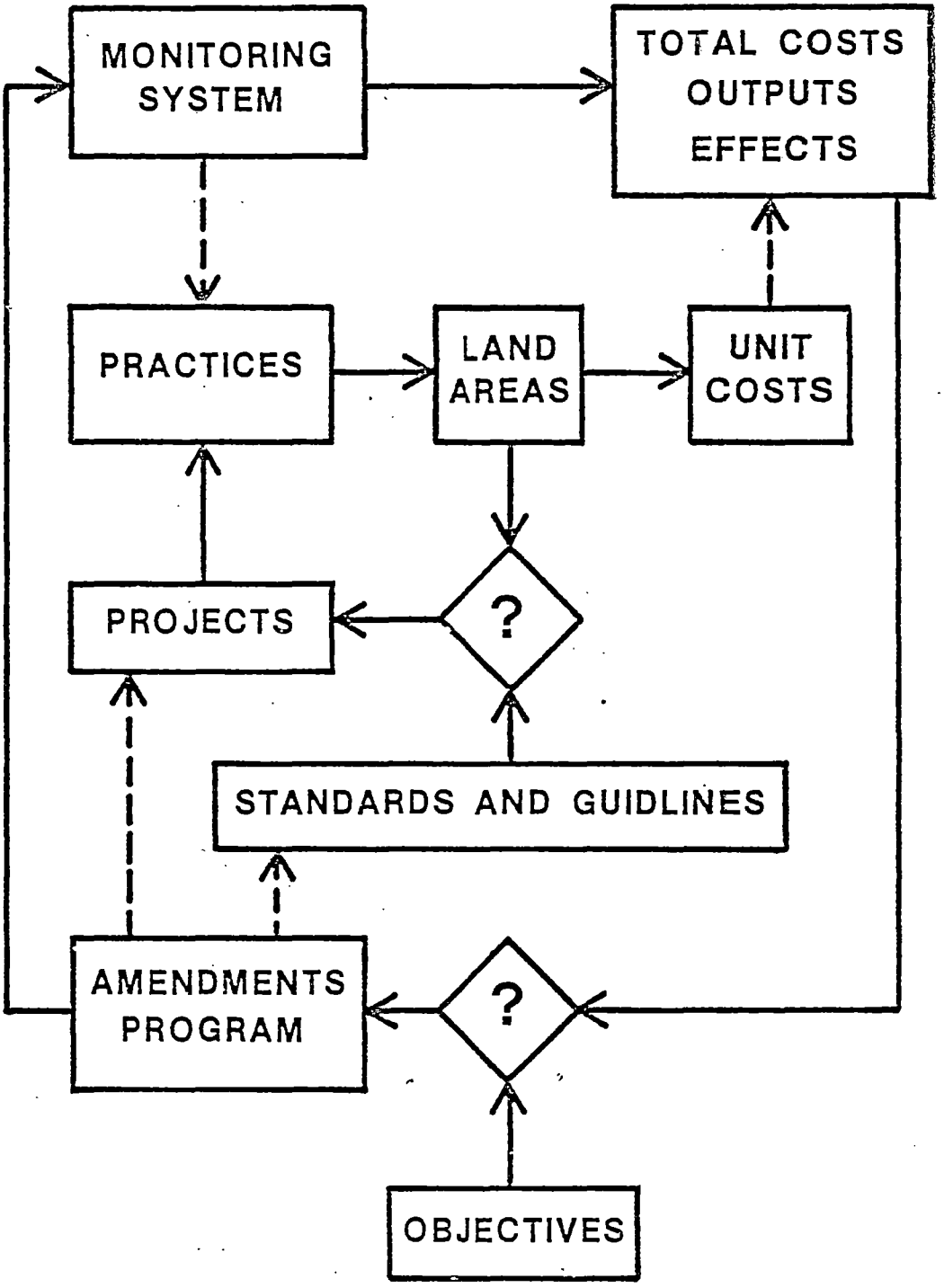

Figure 4.--A two-level closed-loop system which controls practice implementation and modification of the measurement system.

SELECTION OF OUTPUTS AND EFFECTS FOR MONITORING

Certain outputs and effects are established for reporting by national directives (Table 1). Many of these are activities which can be included as part of the practice implementation phase of monitoring, others are more clearly outputs and effects and require some sort of measurement and sampling procedure. Regional directives may also specify some additional outputs and effects which must be reported, and each Forest may establish others for their own needs.

In specifying outputs and effects to be monitored, it is important to keep in mind that the monitoring system should relate to decisions that have been made or will be made. Thus any output or effect which is not related to a decision which can be made about management of the Forest has no real meaning in the monitoring system. As a ridiculous example, it would make no sense to monitor the elevation of the highest peak on the Forest unless we contemplated some management which might change that elevation.

In selecting items to be monitored, it may also be useful to consider how precisely we are able to measure an output or effect and compare this to the probable maximum change that could result from management. If something cannot be measured closer than ± 50%, and the maximum change that could result from management is ± 10%, a monitoring procedure would not give much guidance for management change. If we have some measure of statistical variance for an output, a general rule of thumb is that the expected range of the output, as determined by the analysis of the management situation, should be at least as great as the standard deviation in order for a change to be detected.

Some items to be considered for monitoring may be sensitive public issues, but it seems more realistic to address the issue question directly with a frank public discussion of the measurement problem rather than to engage in a monitoring activity which has significant cost but little or no meaning. On the other hand, any output or effect which will be important in current or future decisions should be monitored. Although it may not be immediately possible to make the necessary management adjustment without a plan revision, collection of background information will make future decisions easier and better.

WHAT TO DO WHEN THINGS GO WRONG

As a Forest operates under a plan, a situation could exist where standards and guidelines can be relaxed or sample size decreased, thus resulting in savings. As an alternative to this happy event, suppose that the monitoring system indicates that the allowable limits of an output or effect are exceeded or that it cannot be determined whether or not the limits have been exceeded. Basically there are three options: (1) amend the standards and guidelines, (2) increase the sample size, or (3) revise the plan (Figure 5). Each of these options will have its own costs and likelihood of success.

As a first step, it should be determined whether or not the standards and guidelines are being met. If not, the annual program and resultant projects should be changed to bring projects into compliance with standards and guidelines. This will be straightforward if standards and guidelines specify how practices are to be implemented. Without such compliance there is little basis for making further judgments.

Table 1.--PROJECTED NATIONAL FOREST SYSTEM PROGRAM OUTPUTS, ACTIVITIES, AND COSTS ADAPTED FROM FSM 1921.29.

OUTPUT/ACTIVITY	UNIT OF MEASURE	OUTPUT/EFFECT OR ACTIVITY
RECREATION Developed Recreation Use (Includes VIS)	Recreation Visitor Days	Output
Dispersed Recreation Use (Includes Wildlife and Fish)	Recreation Visitor Days	Output
Trail Construction/Reconstruction	Miles	Activity
WILDERNESS Wilderness Management	Acres	Activity
WILDLIFE & FISH Wildlife Habitat Improvement	Acre Equivalents	Activity
Anadromous Fish Improvement	Pounds	Output
RANGE Grazing Use (Livestock)	Animal Unit Months	Output
TIMBER Programmed Sales Offered	Board Feet (MMBF)	Output
Reforestation	Acres	Activity
Timber Stand Improvement	Acres	Activity
WATER Meeting Water Quality Goals	Acre feet	Output
MINERALS Minerals Leases and Permits	Operating Plans	Activity
HUMAN & COMMUNITY DEVELOPMENT Human Resources Programs	Enrollee Years	Activity
PROTECTION Fire Management Effectiveness Index	Dollars/Thousand Acres	Activity
Fuel Breaks & Fuel Treatment	Acres	Activity
LANDS Land Purchase and Acquisition Excludes Exchange	Acres	Activity
SOILS Soil & Water Resource Improvement (Improved Watershed Condition)	Acres	Activity
FACITLITIES Road Construction/Reconstruction (Arterial, Collector)	Miles	Activity
Returns to Treasury	Dollars	
COSTS-All	Dollars	
Captial Investments	Dollars	
Backlog	Dollars	
Total Approp.	Dollars	
Allocated Funds	Dollars	
Total NFS	Dollars	

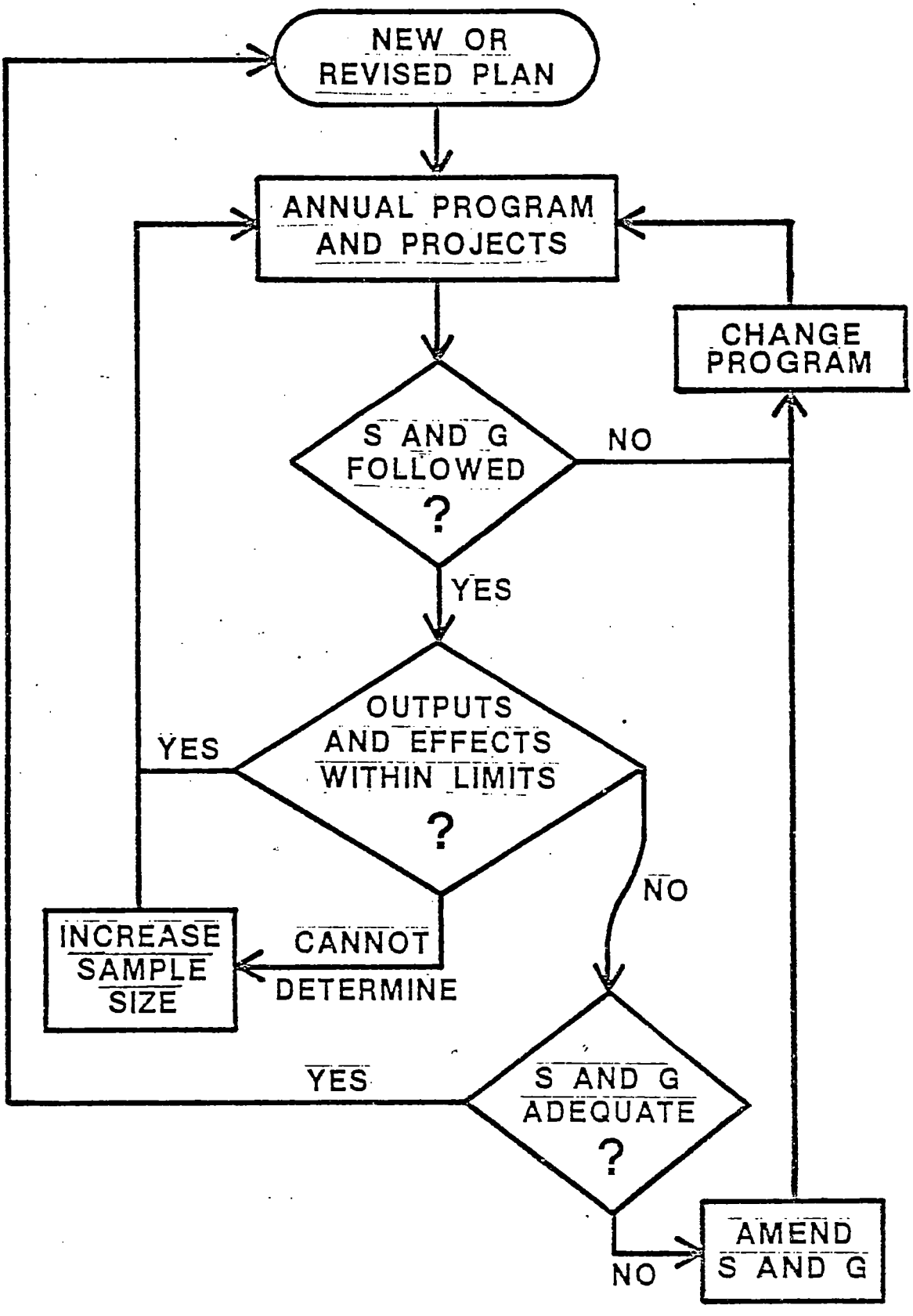

Figure 5.--Flow chart for amending the monitoring scheme.

If the program and projects are in compliance, then the question of outputs and effects being within limits becomes relevant. At this point, the sample size (n) should be examined to determine whether or not it is adequate to detect the output or effect within the required precision. If not, the sample size should be increased.

If the standards and guidelines are being met and the sample size is adequate but the output or effect is still beyond limits, then the question of possible amendments to the standards and guidelines should be raised to determine if the necessary adjustments can be made to projects and practices. Failing adequate corrective action at this point, the only remaining option is to revise the plan.

It is likely to be the usual case that amending the sample size and standards and guidelines will be less costly than the plan revision. It could be, however, that the sample size could become so large or standards and guidelines so restrictive that plan revision is a viable option; in this event a revision prior to the usually required review would be in order.

SAMPLE SIZE FOR MONITORING

Different alternatives represent subregions of the total feasible management region (Figure 6). Alternatives are developed by establishing (or relaxing) a set of constraints; a different set of constraints will result in a different plan. Since selection of a plan represents a commitment to following one of the subregions in preference to other subregions, confirmation that a given plan is being followed requires an ability to distinguish among subregions.

The linear programming solution used in planning finds a set of prescriptions which meet the assigned constraints. With this analytical base for planning there is no provision that allows a change of prescriptions and at the same time remains within the plan. Therefore, a criterion for plan monitoring should be to determine whether or not the constraints have been exceeded. Some constraints will be very demanding, while others will leave more freedom of action. In terms of linear programming problems, the amount of freedom is indicated by the slack (or surplus) variables. These slacks are very important because they describe the amount by which a constraint can change without changing the land allocation (Figure 7). With large slack, it is relatively easy to stay within the constraints, but with small slack, it is more difficult.

Although the slack variables represent one means of determining critical monitoring requirements, other requirements, such as water quality standards, may also be important. Regardless of how the requirement has been established, the ability to detect whether or not an allowable range has been exceeded is a conventional problem in sampling. Basically, for variable i, the difference which can be detected is expressed by the equation $d_i = t_\alpha \sigma_i / \sqrt{n_i}$ where d_i is the detectable difference, t_α the appropriate value of the t distribution for probability α and sample size n_i, σ_i the standard deviation of the population, and n_i the number of observations. Solving for n_i gives

$$n_i = t_\alpha^2 \sigma_i^2 / d_i^2 \quad .$$

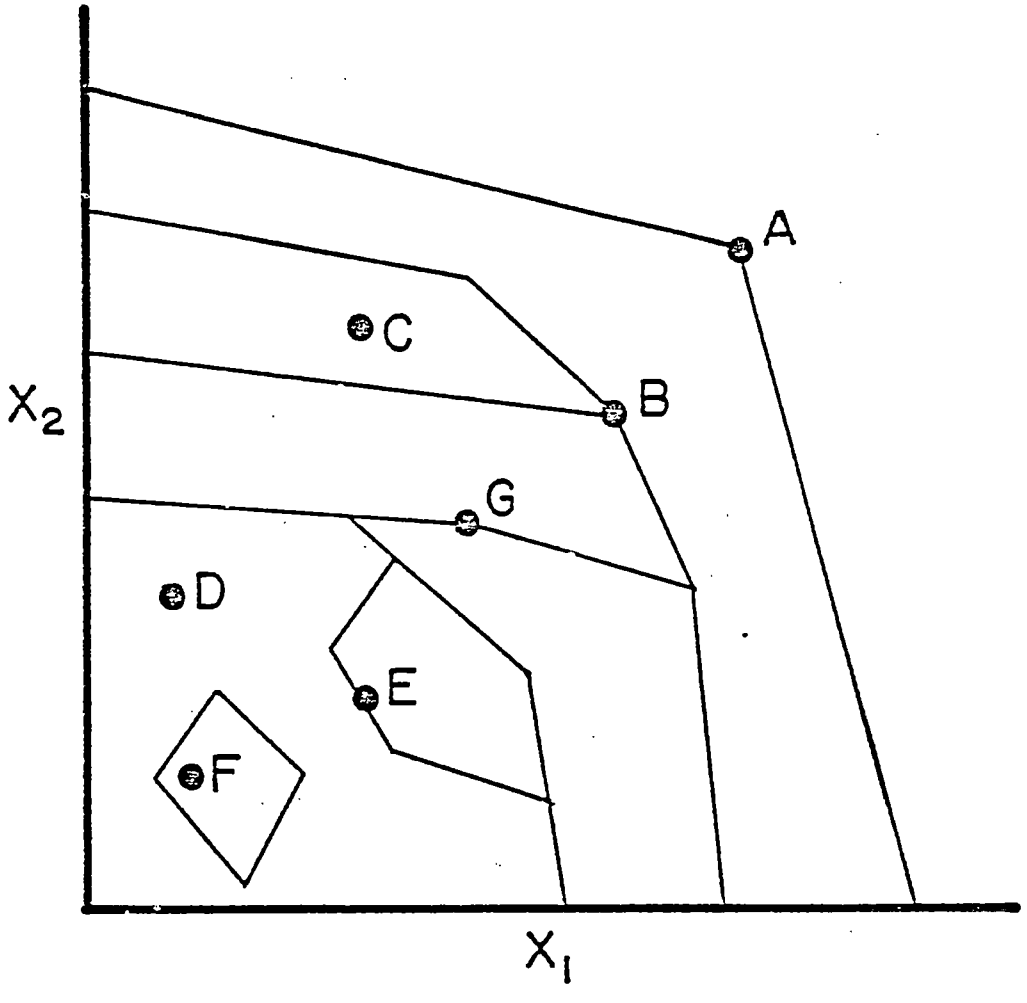

Figure 6.--Illustrative example of dividing the total feasible management region into subregions through the use of constraints. Where labeled points occur at the intersections, the solution is constrained by dimensions represented here; where points occur elsewhere, the solution is constrained by other dimensions.

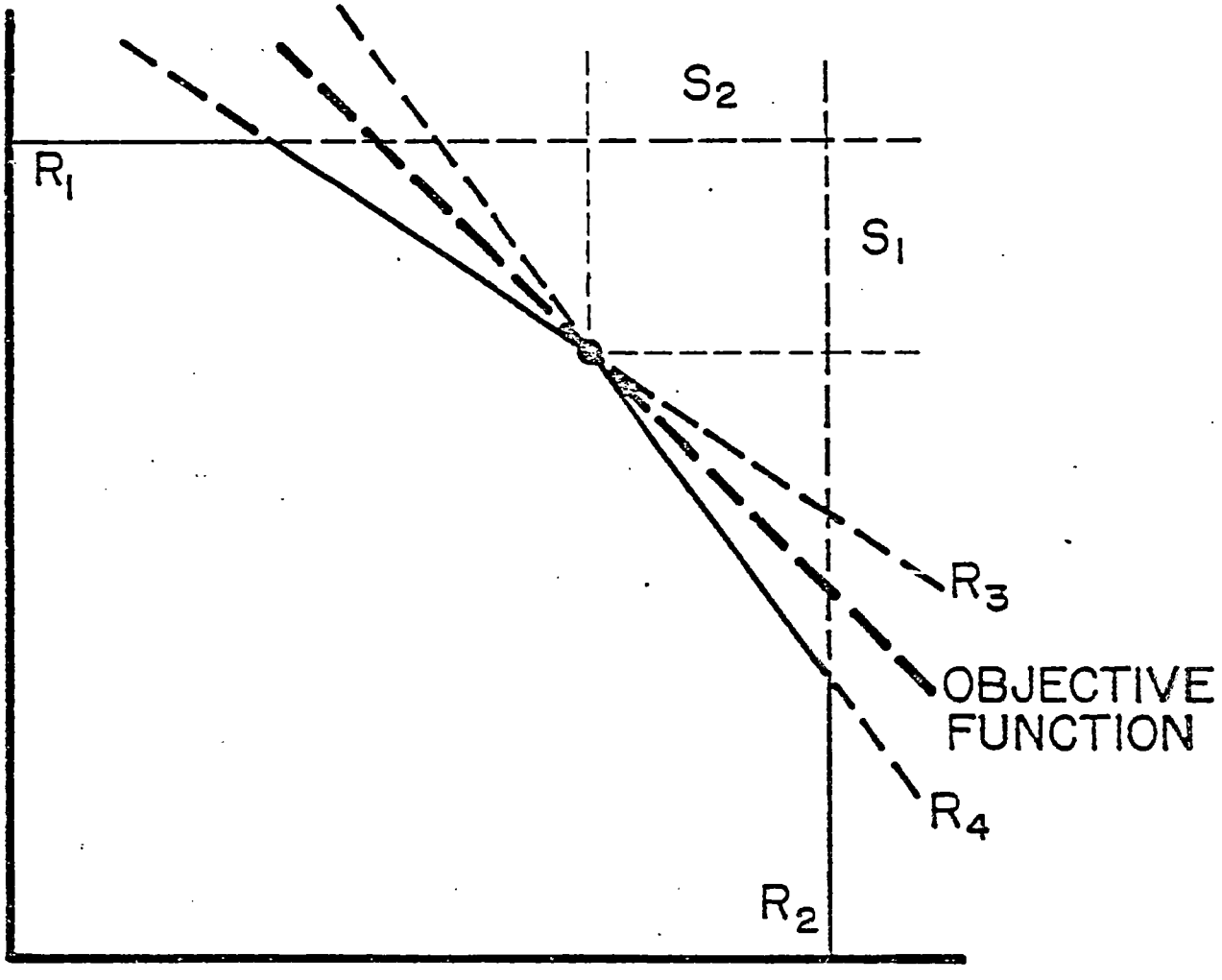

Figure 7.--Representation of resource or other constraints (R) and slack variables (S). Slacks for the resources represented by the intersection at the solution point are zero.

A typical value of t for large n and $\alpha = 0.05$ is 1.7; thus t_α^2 is approximately 3 and $n_i = 3\sigma_i^2/d_i^2$ is a reasonable approximation. If the d_i's are equated to linear programming slack variables, there will be a problem with zero slack and the resultant division by zero. To avoid this problem, d should be defined as somewhat greater than the slack value by the addition of the number 1, or other suitable number depending on the dimensions of d and σ.

With the equation

$$n_i = 3\sigma_i^2/d_i^2 \quad ,$$

the monitoring plan for each alternative is made explicit. It should be clear that alternative strategies with low ratios of σ^2/d^2 will be favored, thus plans with large slack values, especially for variables with high variance, will be preferred. If a slack variable for an alternative plan is zero, the number of observations required to monitor plan performance will be very large; it follows from this that zero slack can only be tolerated with variables that have low variance or low observation cost, or both. Savings from development of measurement methods with lower cost or lower variance can be evaluated by calculating the savings that would result if costs or variances were lowered.

In some cases sample size can be reduced by utilizing the correlation between the sampled output or effect and some other output, effect or activity. Suppose that a timber harvest report is required, and there is a significant correlation between timber harvest and sediment production. The variance estimate used to determine sampling precision for sediment production can be found by

$\sigma_a^2 = \sigma^2(1 - \rho^2)$, where σ_a^2 is the adjusted variance, σ^2 the unadjusted variance, and ρ the correlation coefficient between timber harvest and sediment production. Similarly, the activity of road construction might be used to determine the adjusted variance. Utilizing any correlated information can in many cases reduce the sampling required to adequately monitor an output or effect. This procedure does require that any correlated information be collected on a sample basis so that the correlation coefficient can be

calculated. Also note that if there is a perfect correlation then $\rho^2 = 1$ and only one of the variables needs to be sampled.

MONITORING COST

With the cost of an observation c_i, the cost of determining whether or not a difference has been exceeded is $3c_i\sigma_i^2/d_i^2$. However, plans have multiple constraints, and each must be evaluated to determine whether or not the plan is being followed. Thus the total cost of monitoring for a given plan, K, with I constraints is

$$3 \sum_{i=1}^{I} c_i \sigma_i^2 / d_{iK}^2 \qquad [1]$$

Note that c_i and σ_i^2 do not need to be subscripted by K since these values are supposedly constant across plans. (The relevant value of σ_i^2 to use here is the adjusted value after correlation effects are accounted for.) However, the values of d_i will be different for different plans, and thus d_{iK} must be indicated. In fact, the values of d_{iK} will probably vary over time because of the coefficients and structure used in the linear programming model. Certainly the monitoring costs must be considered over time. The complete expression is, therefore,

$$m_{K\tau} = .3 \sum_{i=1}^{I} c_i \sigma_i^2 / d_{iK\tau}^2 (1 + r)^{\tau} \qquad [2]$$

where $m_{K\tau}$ is the total monitoring cost for plan K at time τ, and r is the discount rate. Similarly, the value of present net worth z' for any time period τ and plan K, adjusted for monitoring costs, is $z'_{K\tau} = z_{K\tau}/(1 + r)^{\tau} - m_{K\tau}$, where $z_{K\tau}$ is that portion of the present net worth for plan K which accrues in time period τ. Without consideration of monitoring costs, the vector $z_{K1}, z_{K2} \ldots z_{K\tau}$ is the optimal path over time given the set of constraints for plan K. However, with the addition of the monitoring cost the original solution may reveal some time periods with difficulties because of high monitoring cost (Table 2).

Table 2.--Display of adjusted present net worth values by time period.

	Alternative Plan			
Time Period	1	2	3	4
1	z'_{11}	z'_{21}	z'_{31}	z'_{41}
2	z'_{12}	z'_{22}	z'_{32}	z'_{42}
3	z'_{13}	z'_{23}	z'_{33}	z'_{34}
4	z'_{14}	z'_{24}	z'_{34}	z'_{44}
5	z'_{15}	z'_{25}	z'_{44}	z'_{45}

ALLOCATION OF MONITORING OBSERVATIONS

As discussed in previous sections, the confidence limits and therefore the number of observations for a monitoring sample are defined for the entire Forest watershed, allotment or other appropriate area. Some outputs and effects, such as standing volume of timber or weight of forage, are located on specific land areas, however, and when this is the case the total number of observations should be distributed in accordance with expected production of the output or effect being sampled.

Consider, for example, a sampling procedure for timber volumes. The output for each capability area is the estimated volume per acre times the acres of the capability area. If the calculated total number of observations required for adequate sampling is n_i then observations should be distributed by first determining the weighted area:

$$Wa_j = \sqrt{ca_j \; a_j}$$

where Wa_j is the weighted area, ca_j is the acreage of the j^{th} capability area and a_j is the expected volume per acre on the capability area.

The ratio of capability area weight and weighted total area is used to proportion n_i among capability areas. Thus,

$$n_{ij} = \frac{n_i \; (Wa_j)}{\sum_{j=1}^{J} Wa_j}$$

would indicate the number of observations per capability area to be n_{ij}. Assignment of observations to capability areas for different outputs and effects will likely be different for each output and effect since both the relative expected production and the number of observations will be different in each case. Consideration should also be given to the sampling procedure established for the national RPA assessment; it may well be that in some cases the RPA requirements are sufficient for Forest level output sampling.

SAMPLE SIZE WITH MULTIPLE AND SELF-CORRELATED OUTPUTS AND EFFECTS

For a given difference that must be detected, the required sample size is determined by the variance of the population being sampled as pointed out in the previous sections. The sampling precision can be increased if we have knowledge of other factors which are related to the population. If we can calculate a correlation coefficient ρ between two outputs and/or effects, then the variance estimate that must be considered is

$$\sigma_a^2 = \sigma^2 \; (1-\rho^2) \qquad [3]$$

been widely used for these purposes in the past, but application are growing (see references at the end of this report for applications in hydrology, continuous forest inventory and fisheries management). If we are dealing with a single output or effect which is self-correlated in time, calculation of the Kalman gain is equivalent to calculation of the auto-correlation coefficient using the well known Box-Jenkins auto-regressive moving average approach (Box and Jenkins 1970). Since the Box-Jenkins models are constrained to single variables, however, we will not elaborate here on their use, but will use a single variable case to help explain the Kalman gain as outlined in the following steps:

(1) Set a year counter k at k = 1 and record the output x and variance σ^2.

(2) Make an estimate $\hat{x}$ of the output for year k + 1 based on x at time k. This estimate can be derived in any fashion, perhaps through a simple annual multiplier or more complex prediction. For simplicity, let us assume that each year will be the same as the previous year, thus the multiplier will be 1 and $\hat{x} = x$.

(3) Compute the predicted variance at year k + 1 as $\sigma^2 = \sigma_e^2 + \sigma_\omega^2$. Since σ_ω^2 is the management effects prediction error, we must have some information on how well we are able to predict the outputs. If we are able to predict the ouput exactly, then $\sigma_\omega^2 = 0$.

(4) Compute $K = \sigma_e^2/(\sigma_e^2 + \sigma_v^2)$ where σ_v^2 is the measurement and sampling error within any time period.

(5) Make a measurement of the output indicated by y, and update the output x by the equation $x = \hat{x} + K\ (y - \hat{x})$.

(6) Compute the adjusted variance $\sigma_a^2 = \sigma_e^2\ (1 - K)$.

(7) Set $k = k + 1$, $\sigma^2 = \sigma_a^2$, and return to Step 2.

With this approach we continue to get better estimates of σ^2 as we collect more data over time. The Kalman approach can be extended to the multivariable case by the use of the elementary matrix manipulations of addition, subtraction, multiplication, inversion, and transposition. For a description of these matrix manipulations see any basic text on matrices and for a good description of the Kalman filter calculations see Jazwinski (1970, p. 269-272).

The ordinary calculations of the Kalman filter assume that the prediction error ω can be distinguished from the measurment error v. If this is not so, we need a statement of the relationship of ω and v as specified in the innovations approach of Kailath (1968).

CALCULATION OF AN OPTIMAL MONITORING POLICY

(This section will be completed by September 30, 1981.)

where σ_a^2 represents the adjusted variance, and ρ^2 the square of the correlation coefficient between the two variables.

The value of ρ is calculated by the original variances and covariances

$$\rho = \frac{\sigma^2_{12}}{\sigma_1 \sigma_2}$$

where σ^2_{12} is the covariance between population 1 and population 2. Instructions on this calculation can be found in any elementary statistics book. If we have measured several outputs and/or effects, ρ could be a multiple correlation coefficient. In addition to interpreting ρ as the correlation between two outputs and/or effects, it could be viewed as the correlation of a single output and/or effect with itself in consecutive years.

Instead of using simple correlation coefficients, we can make adjustments by other means, and it may be desirable to do so. For example, if one of the outputs or effects is constant, the variance will be zero and the correlation coefficient cannot be calculated. In addition, we may want to use more information, such as the correlation with several other variables, some of which are self-correlated over time. Annual management action may also influence the output or effect. It would also be handy to be able to less frequently make some measurements that are difficult or expensive. With these more complex problems, a useful, more general formulation is $\sigma_a^2 = \sigma_e^2 (1 - K)$ where σ_e^2 is the unadjusted expected variance and K is the "Kalman Gain" calculated as

$$K = \sigma_e^2/(\sigma_e^2 + \sigma_v^2)$$

where σ_v^2 is the variance due to measurement error. Note that if there is no measurement (or sampling) error, i.e., $\sigma_v^2 = 0$, then $K = 1$ and $\sigma_a^2 = 0$. Thus, if there is no measurement or sampling error, there is no need to make any observations on this output or effect.

The expected variance σ_e^2 is calculated by $\sigma_e^2 = \sigma^2 + \sigma_\omega^2$ where σ_ω^2 is the error in prediction of management effects. If management effects are estimated with absolute precision (except for measurement or sampling error), then $\sigma_\omega^2 = 0$ and σ_e^2 will be just σ^2. On the other hand, imprecise prediction of management effects will make both σ_ω^2 and σ_e^2 larger.

The Kalman gain does essentially the same job as the square of the correlation coefficient and both have values from 0 to 1. Use of the Kalman gain has not

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